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THEORETICAL MODEL ATMOSPHERES OF VENUS

by Robert B. Owen

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Huntsville, Ala.

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THEORETICAL MODEL ATMOSPHERES OF VENUS

SUMMARY

From a survey of past and present literature, a summation of various models of the atmosphere of Venus is presented. It is shown how these models were formed and eliminated; and a final model, apparently more consistent with recent observations, is advocated. This model, one of the greenhouse variety, indicates more extreme surface conditions than have been previously suspected.

SECTION I. INTRODUCTION--THE CHANGING CONCEPT OF THE ATMOSPHERE OF VENUS

Through the years man's estimations of Cytherean atmospheric conditions have varied drastically. Telescopic observations [2] were stymied by vast opaque clouds which completely hid the surface, and thus the only perceivable features were atmospheric bands and markings. This data deficiency spawned an almost unlimited variety of planetary models. Since nearly any result desired could be extrapolated from such meager knowledge, the consequential guesses about the origin of these strips ranged from theories of fantastically huge artifacts created by hypothetical Cythereans to opinions which presented the traces as mere optical effects [3].

The range of these models became a bit restricted when the utilization of improved instruments and spectral analysis made more information available. Recently, a model which may be considered as fairly accurate has emerged from spectral [4], radio [5][6], radar [7][8][9], and Mariner II measurements. While many details are still doubtful, it is believed that a single model, basically identical with the actual atmosphere of Venus, has finally been conceived. In this report, past models will be presented, and the change and modification leading to the present conception will be shown.

SECTION II. EARLY MODELS

A. CARBONIFEROUS SWAMP MODEL, Figure 1 (a)

This model, perhaps the most appealing to the layman, followed hard upon the discovery of gigantic, murky clouds in the Venus atmosphere. From analogy with Earth conditions, it appeared obvious that clouds of the observed size and thickness could only be great rainclouds [10]; and the resulting hot, humid atmosphere would consequently compose swamp-like surface conditions [11].

Unfortunately for much of the popular literature of the time, spectral analysis [12] revealed that the atmospheric water content could not possibly be high enough to allow the existence of such a surface.

While searching for water [10], a high CO_2 content was accidentally found in the atmosphere. The CO_2 concentration was expected to be rather minute because of the Urey equilibrium, a reaction between CO_2 and surface silicates, which occurred as follows:

$$MgSiO_3 + CO_2 \overset{H_2O}{\leftrightarrows} MgCO_3 + SiO_2$$

and

$$CaSiO_3 + CO_2 \overset{H_2O}{\rightleftarrows} CaCO_3 + SiO_2 \quad .$$

Since this reaction should take place under the conditions of the model, an impasse was reached between model and observation. Thus the colorful, carboniferous swamp, swarming with fauna, has been abandoned by technical literature and is preserved only in Edgar Rice Burroughs' novels.

B. DESERT MODEL, Figure 2

Since liquid water is required as a catalyst in the Urey equilibrium, this model proposes a total lack of water as an explanation of the absence of that reaction. Thus the surface, as suggested by Öpik in 1956 [13], would be a hot, dry desert. The great amount of CO_2, which is estimated to be more than 40 per cent of the atmosphere, and the nonexistence of O_2 and H_2O is taken to indicate an organic void, the antithesis of the swamp model. The clouds are dust clouds, and the air mass above them is approximately 15 per cent that of Earth. Such

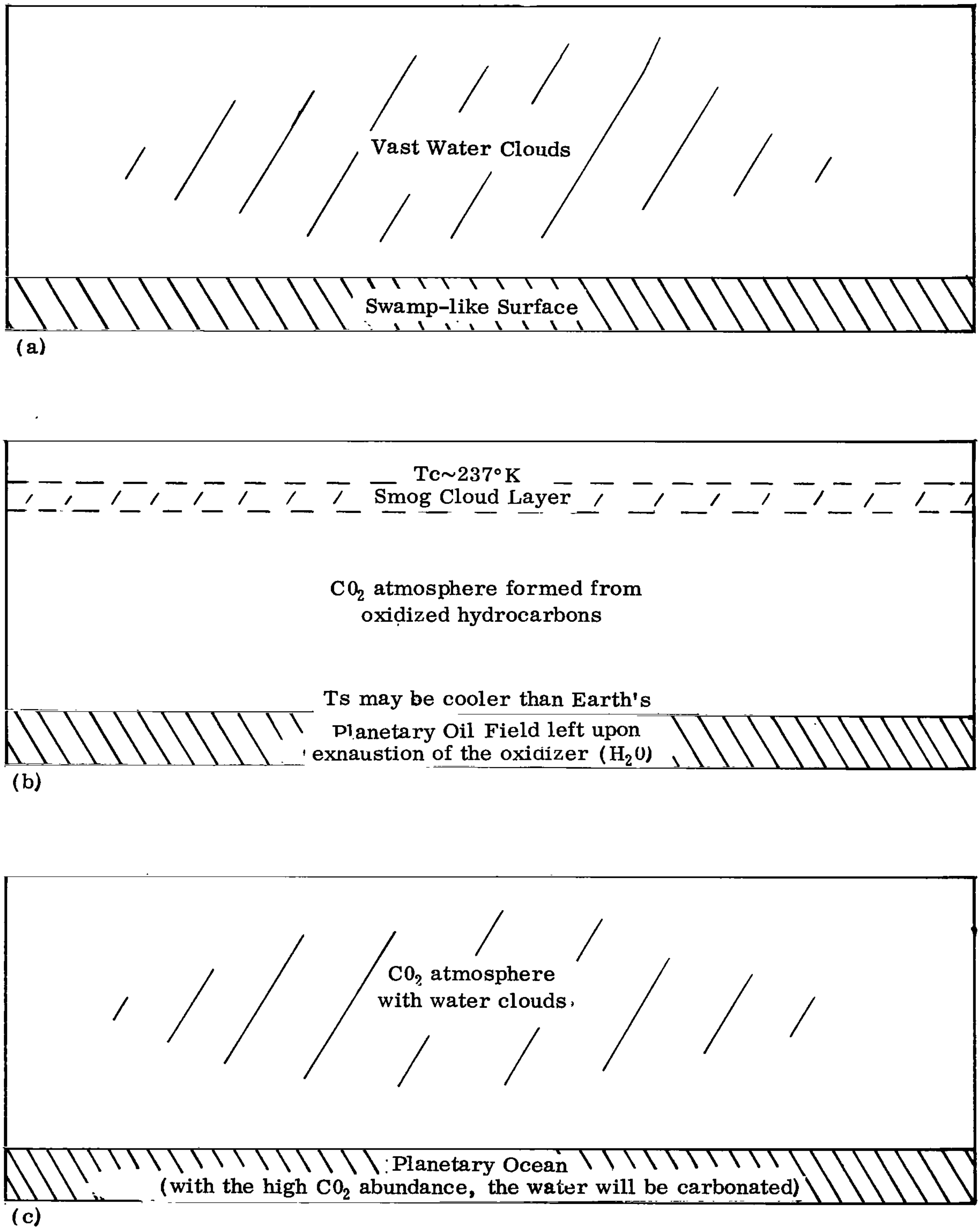


FIGURE 1. PROPOSED SURFACE MODELS: (a) CARBONIFEROUS SWAMP MODEL; (b) CRUDE OIL MODEL; (c) GLOBAL SELTZER OCEAN MODEL.

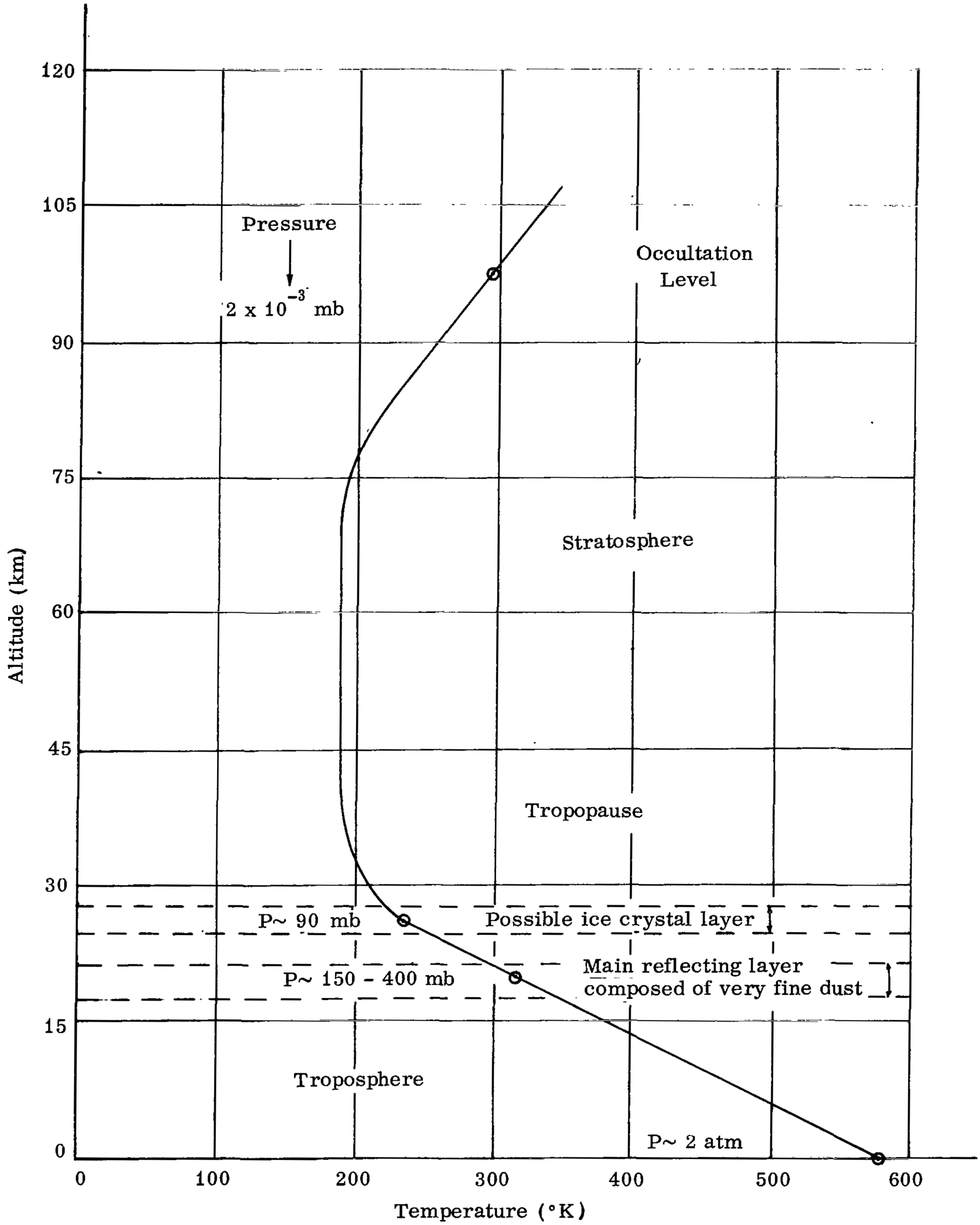


FIGURE 2. THERMAL STRUCTURE OF THE DESERT MODEL

clouds could not contain water, since any rain would remove dust and eventually form a clear atmosphere. The yellow color of Venus should also eliminate the possibility of atmospheric water. The cloud top is considered to be at a height of approximately 20 km and at a temperature of approximately 317° K. The period of rotation should be about 10 days, and the surfaee pressure approximately 2 atmospheres.

This model was advocated for some time, in spite of a controversy over the water content of the atmosphere. Many, such as Kaplan [14], Urey 1959 [15], and Sinton [16], favored the existence of an ice-crystal layer, the existence of which would necessitate some atmospheric water. This theory had some positive evidence which indicated that water might be present. Lyot [10] found that the polarization curve of water droplets could be made to resemble that of Venus. While other substances could have such optical properties, this rather poor fit is the best which has been obtained.

To further the discordance, the yellow color of Venus can be explained in several ways which do not require the absence of water. Certain molecules, such as CO_2^+ and CO^+, almost have to exist in the atmosphere; and their absorbent qualities probably contribute to the yellow effect [15]. Also, spectral agreement [12] between the measurements of Harris, Hall, and Blacet and of Heyden imply the presençe of N_2O_4. This absorber could account for the failure to detect O_2 as well as for the color effects.

The model was finally discarded when observations by Spinrad [17] and others revealed high pressures which were incompatible with the proposed planetary conditions. Also, a satisfactory mechanism for the maintenance of the high surface temperatures was never incorporated into the model.

C. GLOBAL SELTZER OCEAN MODEL, Figure 1 (c)

This model was proposed by Menzel and Whipple [18] in an attempt to account for the absence of the Urey equilibrium. It was assumed that the entire surface was covered with water; and since this integument would segregate the silicates from the CO_2, any reaction between the two would be prevented.

With the high CO_2 content of the atmosphere [10], the oceans would be carbonated. These seltzer oceans would produce water clouds. Thus the question of atmospheric water content became a controversial point in this model. Water vapor [18] in suitable quantity could be available in an atmosphere so as to agree with both polarization and reflection characterics. The necessary droplets are both uniform in size and rather large for air-borne dust. Earth experience indicates that the only probable substance is water.

However, radar measurements indicated a rough surface [8], and the value obtained for mean surface reflectivity [19] was such as to rule out water at the reflecting point. Also, temperatures above the boiling point of water were observed at centimeter wave lengths [20] [21] [22]; and when these measurements were firmly established as thermal by Mariner II [23] [24], the model became impossible.

D. PLANETARY OIL FIELD, Figure 1 (b)

Advocated by Hoyle and Mintz, this model used a global crude oil field to separate the CO_2 and the silicates. This ocean is created by assuming a great excess of hydrocarbons over water on primitive Venus [10]. CO_2 was produced when the hydrocarbons were oxidized by the H_2O. Upon the exhaustion of the water, the remaining hydrocarbons coated the surface. The visible cloud layer is thus composed of smog, and the resulting surface temperatures may be colder than those of Earth.

By assuming that CO_2 is the only absorbent, Mintz [25] calculated the radiative equilibrium temperature and found the atmosphere to be convectively stable with a cloud top temperature of approximately 237°K. The small temperature gradient is attributed to the large heat capacity of the crude oil ocean. Visual and ultraviolet observations indicate that the general circulation consists of low-level horizontal cells which transport heat from the low to the high latitudes and from the day to the night side. The entire system is surmounted by a circumpolar vortex.

The model appears fairly valid as long as low surface temperatures may be assumed. In the absence of water, hydrocarbon oceans are not unreasonable. Radar measurements [19] determined a dielectric constant of $4.1 {}^{+1.9}_{-0.9}$ for the surface; and since the value for oil is approximately 3, these observations indicated a possible oil field.

However, some cloud temperature measurements gave rise to an incongruity [10], since at such temperatures the vapor pressure of hydrocarbons would be such as to permit spectroscopic identification. Also, Moore [3] maintained that the radial circulation pattern was because of optical effects. The model was eliminated when Mariner II measurements [23] [24] indicated that surface temperatures were too high to allow the proposed oil field.

SECTION III. RECENT MODELS

A. GREENHOUSE MODEL "A", Figure 3

Radio emissions from Venus [26] [20] indicating black-body temperatures of approximately 600° K have been observed in the 3 to 21 centimeter region. This model assumes that these emissions are thermal and are radiated from the surface. To explain this, the following greenhouse mechanism was proposed by Sagan [27].

Some visible solar radiation penetrates the cloud cover and strikes the surface, which upon being heated radiates in the infrared. This infrared radiation is trapped in the lower atmosphere because of molecular absorption and light scattering in the cloud cover. In this model the 8000 Å $C0_2$ band shows temperatures of approximately 285° K, and the 8 mm band shows temperatures of approximately 350° K, with both arising from somewhere in the atmosphere. The required opacity for this model cannot be due to $C0_2$ alone; however, if 10 gm/cm^2 of H_20 vapor are assumed, infrared opaque conditions are achieved. With a constant H_20 mixing rate and an adiabatic lapse rate, the water vapor will saturate the atmosphere at 36 km. In this model the far infrared radiation will arise from about 35 km, and since this radiation indicates a temperature of 234° K at that level, an ice crystal layer should be formed. Near infrared spectrophotometry by Sinton [16] shows absorption features attributed to ice at the same temperature level from which the far infrared thermocouple radiation arises. Above these cirrus clouds, $C0_2$ ionization as well as N_2 ionization will occur, if any nitrogen exists [28].

There has been much to recommend this model. In addition to Sinton's [16] spectrophotometry, Strong's [27] balloon observations also indicated that the required amount of water vapor existed above the cloud layer. It has been conclusively demonstrated that a fairly dense water cloud layer with ice crystals above it can explain the microwave spectrum and phase effect. Sinton [16] stated that an ice crystal cloud below the visible cloud layer at about 35 km altitude would handle the greenhouse effect nicely. The ice crystal cloud would explain emission at 10 μ [14], and it would also account for the observed albedo of Venus [10]. The theory of radiation, if one assumes a surface temperature of 600° K, implies an ice-crystal layer at 30-40 km, according to Sagan. The small temperature differences observed between the dark and light sides at some wave lengths are explainable by cloud condensing. For example, the 8 mm phase effect would be the result of a cloud layer which appears opaque at millimeter wave lengths and transparent at centimeter wave lengths and is condensable or sublimeable. On the light side the cloud vaporization would increase; thus the attenuation of emission from the surface would decline.

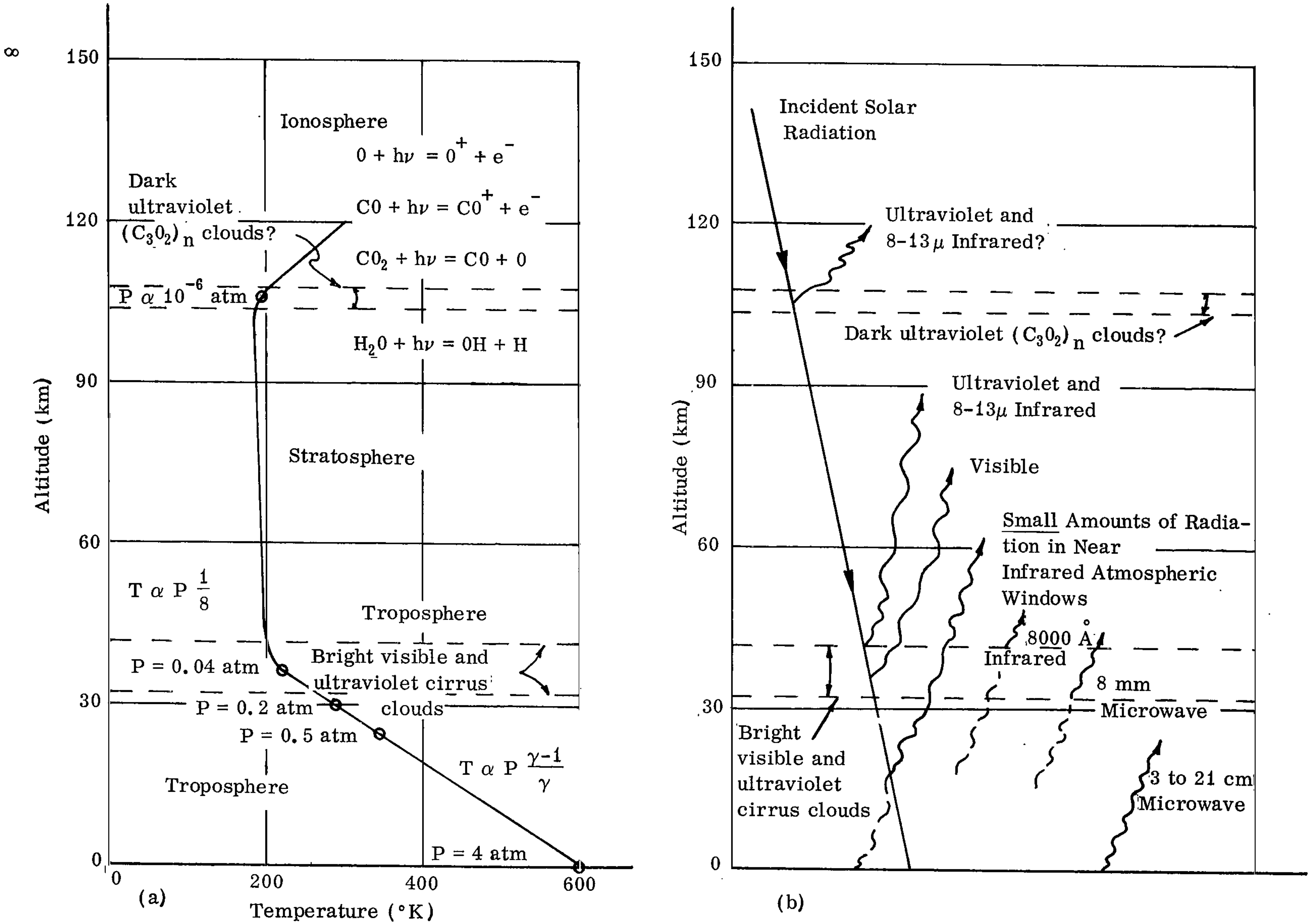


FIGURE 3. GREENHOUSE MODEL "A": (a) TEMPERATURE VS ALTITUDE: (b) RADIATION LEVELS.

On the basis of assumed radiative transfer, that is, that the optical atmosphere would scatter radiation isotropically, a composite rotational temperature of 285 ± 9° K has been derived from the CO_2 bands in the 8000 Å region. By considering the effects of pressure broadening of the spectral lines in an adiabatic atmosphere, the temperature of the bottom of the indicated bands has been found to be approximately 320° K. These rotational temperatures must come from deeper levels than the thermocouple temperatures, probably from below the visible cloud layer. This is evidence for the transparency of the visible cloud layer in the near infrared.

The absence of the Urey equilibrium is compatible with this model, since the necessary liquid water catalyst probably does not exist under the conditions indicated by the greenhouse effect. The yellow color of Venus may be explained by the effects of Rayleigh scattering or the presence above the cloud layer of the polymer of carbon suboxide or both [29].

Ohring [30] has made some new radiation balance calculations in which the cloud cover was more strongly considered. His results indicate that the clouds enhance the greenhouse effect greatly, and it is implied that the requirements for large amounts of infrared absorbing gases are diminished as the amount of cloudiness increases.

Some difficulties arose when some observations by Spinrad [17] indicated that the amount of water vapor in the atmosphere was insufficient to maintain the greenhouse effect. This confliction in measurements produced quite a controversy over the existence or nonexistence of water vapor in the Cytherean atmosphere. Several other incongruities indicate that some modifications are needed or that the model may be completely invalid.

B. IONOSPHERIC MODEL, Figure 4

1. Ionospheric Mechanisms. Since the discovery of Cytherean radio waves which indicated high temperatures, several mechanisms have been proposed which would provide a nonthermal source for the emissions. All models which advocate cool surface conditions must incorporate one of these mechanisms into the system, generally as an ionospheric source of one type or another.

a. Jones' mechanism, Figure 5 (a). In this source [10] the nighttime ionosphere has an $\bar{e}$ temperature of 600° K and an $\bar{e}$ density of approximately $10^9/cm^3$. These values are somewhat higher in the day hemisphere. The 3 to 21 cm emissions are thus radiated by the electrons making free-free transitions.

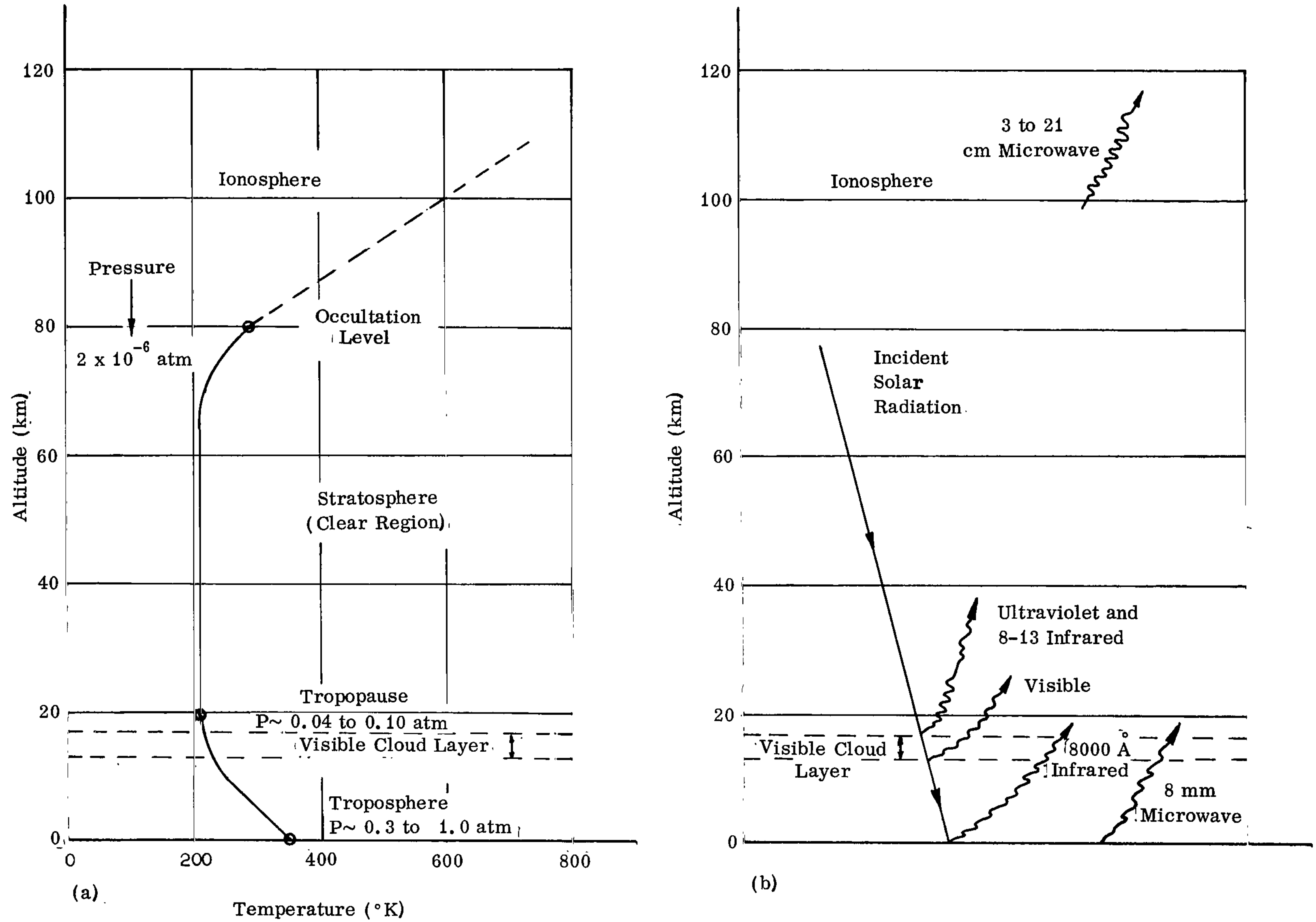


FIGURE 4. IONOSPHERIC MODEL: (a) THERMAL STRUCTURE: (b) REFLECTING LAYERS

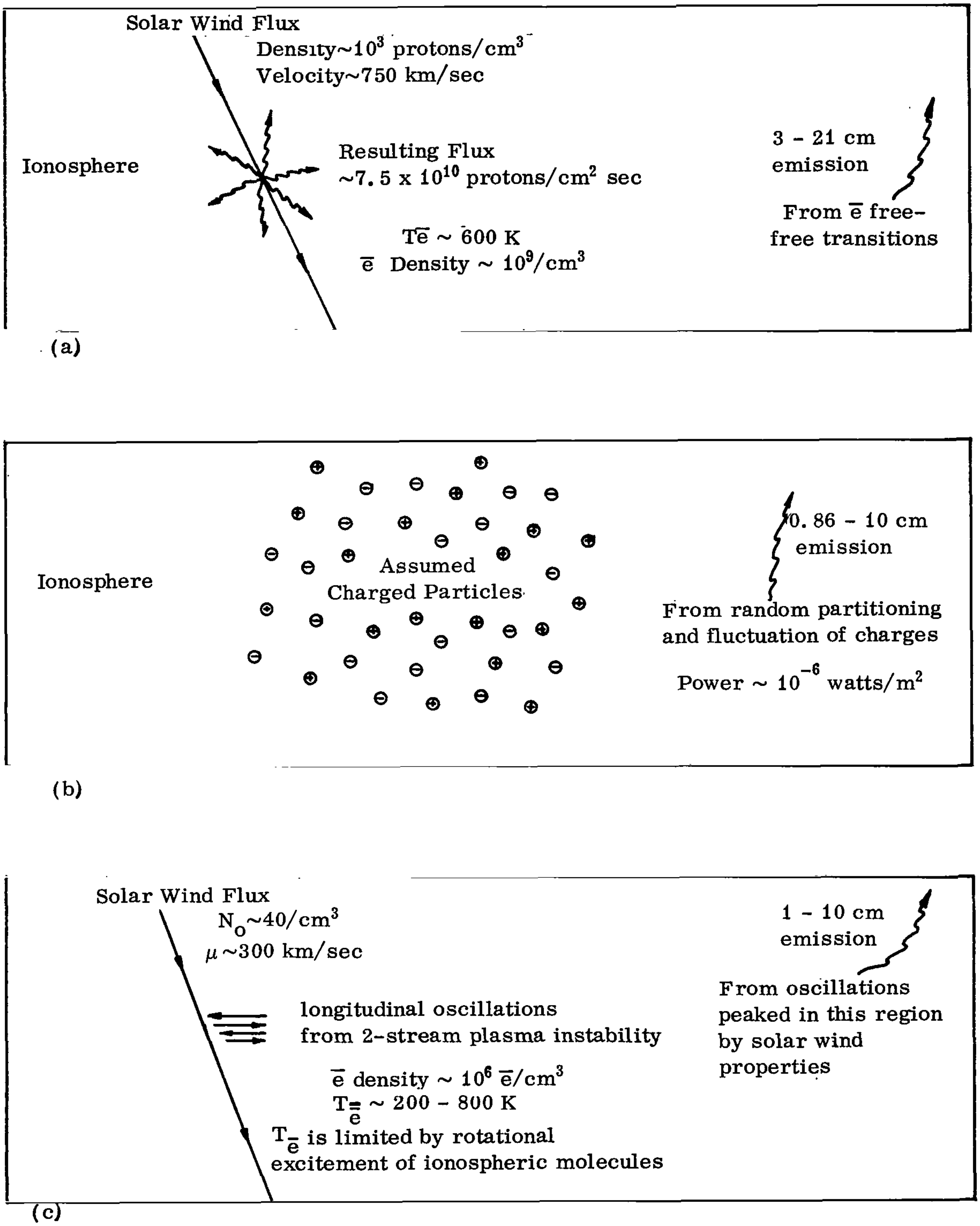


FIGURE 5. PROPOSED MECHANISMS FOR MAINTENANCE OF THE IONOSPHERIC MODEL: (a) JONES' MECHANISM; (b) TOLBERT'S MECHANISM; (c) SCARF'S MECHANISM.

The ionosphere would be opaque at frequencies greater than 3 cm, but would start becoming transparent at 1 cm. At 8 mm (350° K) the emissions would be largely from the surface. This system accounts for microwave spectrum and the phase variations. The far infrared (234° K) is from a cloud layer 15 km above Venus, and the 8000 Å bands (285°K) are from near the surface. Ground level temperature is below that of boiling water and would permit oceans, but in this model the tropopause cloud layer does not consist of water.

This model is rather favorable from the viewpoint of landing possibilities, since it allows cool temperatures. There are several factors in its favor, for example, the neat explanation for phase variations. They may be explained by increased $\overline{e}$ density and temperature on the sunlit side; these results [31] agree with observations by Lebedev Physical Insitute and the National Radio Astronomy Observatory without requiring a drastic departure from an adiabatic lapse rate. Also [32], if surface temperature and $\overline{e}$ temperature and density are allowed to be functions of zenith angle, a fit can be made to about any variation of brightness temperature with phase. For example, assuming that $T_{\overline{e}}$ and T_S do not vary with zenith but that $\overline{e}$ density does, a crude fit to the 1959 8 mm and 3.75 cm phase data can be obtained for the case where the noon e density is three to five times that at night.

Several variations, noted by Kuzmin and Salononovich [21] in which the drift curves of Venus showed anomalously high (1000-1500° K) brightness temperatures, are compatible only with an ionospheric model. These measurements [32], if verified, would provide strong support for the mechanism.

The fact that radar returns [31] have been obtained from the planet would seem to contradict the model, since opacity for free-free transitions increases α (wave length)^2. Thus at radar frequencies the opacity should be very high. However, the assumption of a radar hole in the nightside ionosphere, quite possible on a slowly rotating planet, would account for the echoes.

The mechanism requires a rather high $\overline{e}$ density and a magnetic field 1/30 that of Earth [32]. However, some rather marginal Millstone radar data [31] suggests frequencies near 400 mc, which would indicate the required dark-side $\overline{e}$ density. Also, Mariner II data [24] indicated that the upper limit of the Cytherean magnetic field was approximately 1/10 that of Earth.

There are numerous difficulties in explaining certain aspects of the mechanism. The required $\overline{e}$ density [31] is possible only if the magnetic field is less than 10^{-3} gauss, the highest published value for the solar wind flux is correct, and dissociation recombination is excluded in the atmosphere. If solar electromagnetic radiation is assumed to be the ionization source, recombination coefficients approximately 10^{-14} to 10^{-16} cm^3/sec are required; but since recombination coefficients are characteristically approximately 10^{-12} and dissociative coefficients approximately 10^{-8} cm^3/sec, there appears to be no way of quenching radiative recombination and thus allowing lower rate processes (3-body collisions) to dominate.

Recently, there have been several observations which disagree with this system. Measurements by Drake do not support the fluctuations of Kuzmin and Salomonovich, and he has noted that the microwave spectrum appears quite close to thermic. Also, the phase effects of the model do not agree with Naval Research Laboratory observations. The low surface temperature is inconsistent with the calculations of conditions produced by a greenhouse effect. The far infrared limb-darking curve [33] (Sinton and Strong) was used to determine the thermal stability of the optically accessible atmosphere. The temperature decrease with height obtained from this curve plus the radiative heating pattern argue against a warm stratosphere.

b. Tolbert's mechanism [34], Figure 5(b). In this system, the emission from 0.86-10.0 cm is hypothesized as originating from a random partitioning and fluctuation of the charges on charged particles which are assumed to exist in the atmosphere. Measurements of radiation from particle discharges show a spectrum which is independent of the individual charges. Given a source of an equal number of $\oplus$ and $\ominus$ charges, ions of opposite charges will diffuse and not recombine if their kinetic energy equals or exceeds their potential energy.

It is thus hypothesized that the fluctuation of charges on particles in the Venus atmosphere is of such intensity and frequency of occurrence that the observed flux density is the result of radiation from this source. A spectrum of flux density versus wave length can be obtained through the partitioning of charges between particles that is in agreement with the observed values.

Using a medium Earth rainfall as an example, it may be shown that the spectrum of particle charge and discharge is similar to that spectrum observed from Venus. Power of approximately 10^{-6} watts/m^2 from particle discharge will suffice to duplicate the Cytherean spectrum, whereas the potential radiation power of a medium Earth rainfall is approximately 1.6×10^{-5} watts/m^2. This example shows the order of magnitude and characteristics of radiation which may be expected from particle charge and discharge. The water particles of such a rainfall absorb and attenuate the possible radiation; but many materials with crystalline structures, such as sand or ice, would radiate efficiently. So, given the same particle density distribution, rate of fall, and particle size as occurs in a medium Earth rainfall, the microwave radiation may be explained by the fluctuation of $\overline{e}$ charges on particles, assuming a radiation efficiency 1/10 of that associated with high conductivity particles.

A possible source of the ions for this system would be the highly ionized upper atmosphere and associated large temperature inversion which are suggested by the observed high values for aurora and airglow and by the apparent non-uniformity of cloud height.

c. Scarf's mechanism, Figure 5(c). Assuming that the magnetic field of Venus is small enough to allow a significant fraction of a realistic solar wind flux to flow into the ionosphere and enhance ionization, it is reasonable to expect an $\bar{e}$ density or approximately 10^6 - $10^7/cm^3$ and a normal $\bar{e}$ temperature of approximately 200 - 800° K in the lower atmosphere. It is thus conjectured that (1) a continuous two-stream plasma instability induces longitudinal oscillations which grow until space charge limitations and turbulent break-up occur, (2) that the $\bar{e}$ temperature is limited by rotational excitation of ionospheric molecules, resulting in an intense airglow and no quenching of the instability and (3) that a fraction of the energy in the acoustic mode is then radiated, primarily at the high harmonics of the plasma frequency which have wave lengths near the characteristic wave length of the instability. The known properties of the wind lead naturally to oscillations peaked in the 1-10 cm wave length range, and the total radiated flux is on the order of 0.1 per cent of the incident solar wind flux (2×10^{-3} watts/m^2).

Assuming that the planar ionosphere has uniform density ($N_o = 10^6$ $\bar{e}/cm^3$) and that the solar wind incident on Venus is a cold neutral stream with $N_o = 40/cm^3$ and $\mu = 300$ km/sec, the resulting fluctuations in the solar wind flux occur very slowly compared with t_o; therefore the steady interaction must be regarded as a continuous sequence of initial value perturbations. That is, these density variations grow so rapidly that space charge limitations become significant only in times of microseconds; but since power is still being transferred to the oscillations at these times, the energy must be carried off in other ways. No reliable quantitative description is available for this energy transfer.

The intense Cytherean airglow indicates that much of the solar wind penetrates to relatively low altitudes, so a wind-ionosphere interaction of the type described would seem reasonable. Although such a hydrogen plasma instability tends to quench itself, this aspect is not present when the background contains many molecules such as N_2, CO_2, and O_2 [36], which are expected to be in the Cytherean atmosphere [37]. In addition, turbulent breakup of the density perturbation patterns is possible and likely [35]; this would peak the radiation. This radiation would be enhanced at the high harmonics by the ionosphere pattern.

2. Possible Causes for Ionospheric Emission

a. Dust and sandstorm source, Figure 6 (a). Mintz [38] proposed the following lower atmospheric conditions as a possible cause for emission via Tolbert's mechanism [34].

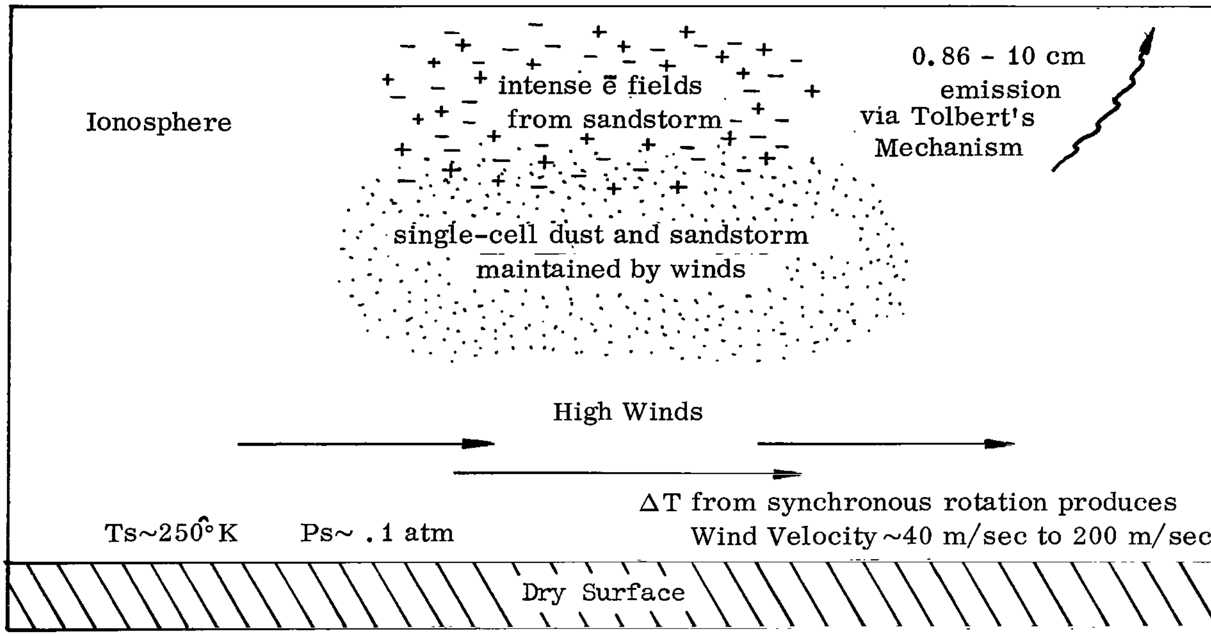
Assuming a surface temperature of approximately 250°K, a surface pressure of approximately 0.1 atmosphere, a lapse rate equal to one-half adiabatic, and synchronous rotation, utilization of gas laws indicates that the surface wind velocity must be 40 m/sec or 90 mph to allow the energy radiated by the dark side to be replaced by energy transported from the sunlit side. By assuming a less stable lapse rate of 9/10 adiabatic, a velocity of 450 mph is obtained. Therefore, if the rotation is synchronous and the surface pressure is low, there will be strong winds.

If the planet is also dry, a fairly safe assumption, this strong circulation could maintain the entire atmosphere as a single-cell dust and sandstorm. This would hide the surface and generate intense electrical fields, which could then be the source of the microwave radiation and would emit as suggested by Tolbert and Straiton.

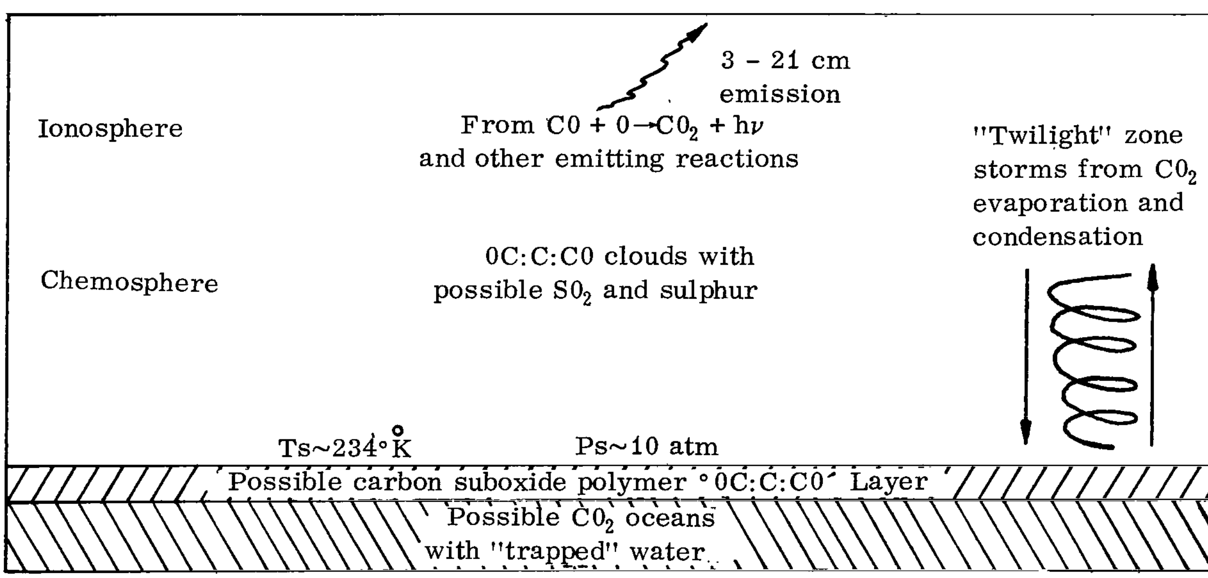
b. Chemical emission as a source, Figure 6(b). Harteck [39] has proposed that the microwave emissions could be caused by chemical reactions which are likely to occur in the Cytherean atmosphere. The existence of a "chemosphere" is advocated, in which such reactions as $CO + O \rightarrow CO_2 + h_\nu$ would emit in the centimeter region.

The atmosphere of Venus is chemically inert. Its major constituents are CO_2, CO, O_2, N_2, and some noble gases. CO_2 is assumed to make up the majority of the atmosphere, with CO and O_2 as minor parts. The presence of oxygen in the atmosphere was established by the Crimean Astrophysical Observatory [36], which based its findings on a slight absorption of solar light. Presence of N_2 and noble gases is considered probable [39], with H_2O almost completely lacking. Assuming an original excess of CO, conversion would have produced carbon suboxide polymer, OC:C:CO. This polymer may now cover the surface, be a main constituent of the clouds via thermal decomposition, and be forming and decomposing in an equilibrium state, thus accounting for the inert atmosphere.

In the chemosphere, a multitude of possible reactions exists. There CO_2 will dissociate into CO and O atoms, while N_2 and CO dissociate at higher altitudes. The radiation chemistry of CO_2 is as follows:



(a)



(b)

FIGURE 6. POSSIBLE CAUSES FOR IONOSPHERIC EMISSION: (a) DUST AND SANDSTORM SOURCE (MINTZ); (b) CHEMICAL EMISSION (HARTECK).

$$CO_2 + h_\nu \rightarrow CO + O \quad \text{or} \quad C + O + O$$

$$CO + h_\nu \rightarrow C + O$$

$$CO + C + M \rightarrow C_2O + M$$

$$C_2O + CO + M \rightarrow C_3O_2 + M$$

$$O_2 + O + M \rightarrow O_3 + M$$

$$C_3O_2 + O \rightarrow CO_2 + C_2O$$

$$CO + O + M \rightarrow CO_2 + M$$

In the lower atmosphere, oxidation of CO would occur by the following $O_2 - O_3$ cycle:

$$O_2 + h_\nu \rightarrow O + O \; (h_\nu \sim 2000 - 2400 \text{ Å})$$

$$O + O_2 + M \rightarrow O_3 + M \; (K = 5 \times 10^{-34})$$

$$O_3 + h_\nu \rightarrow O_2 + O \; (h_\nu \sim 2200 - 2800 \text{ Å})$$

$$CO + O + M \rightarrow CO_2 + M \; (K = 5 \times 10^{-36})$$

$$O_3 + O \rightarrow 2O_2 \; (K = 10^{-14})$$

Because of the dryness of the planet, no H-atoms formed by H_2O vapor photodissociation will be found in the exosphere; but a stationary H-atom concentration equal to approximately 10^5 atoms at 100 km will exist because of the solar winds. Large amounts of CO_2^+ and CO^+ are expected in the ionosphere, with possibilities of more complex ions.

In the chemosphere, assuming that the pressure is approximately 10^{-7} atmospheres and O/O_2 approximately 10, the ratio of CO_2 to CO will be approximately 1/500. Here the far ultraviolet radiation at 1200 - 1900 Å is strongly absorbed, and the O_2 thus formed will be carried to lower regions by diffusion and convection. Reoxidation of CO occurs below the chemosphere via the ozone layer, in which the cycle $O + O_2 + M \rightarrow O_3 + M$ and $O_3 + h_\nu \rightarrow O_2 + O$ takes place until reaction with CO produces CO_2.

In the upper atmosphere, CO which is excited and dissociated by ultraviolet can react with CO, as $CO^* + CO \rightarrow C_2O + O$ or $CO_2 + C$. Thus C_2O does not accumulate in the chemosphere. N_2 will be dissociated into N-atoms which may react with C-atoms from the dissocation of CO to form CN or C_2N_2. Under the action of h_ν, this would polymerize to $(CN)_x$; and assuming the presence of O_2, $(CNO)_x$ will be formed. Such polymers may contribute substantially to the clouds.

Under the proposed conditions, the surface temperature may be as low as 234° K, with a possible surface pressure of approximately 10 atmospheres. With such parameters, CO_2 oceans could exist. Synchronous rotation would make these oceans "traps" for water, and large storms would result from CO_2 evaporation and condensation in the "twilight" zones. Carbon suboxide would consume all the water vapor, so SO_2 could accumulate from volcanic reactions. Sulphur could exist, as well as carbon from decomposed suboxide.

C. AEOLOSPHERE MODEL, Figure 7

This model was proposed by Öpik [40] as a possible mechanism for the maintenence of the observed microwave black-body temperatures of 600° K, which are assumed to be surface temperatures.

The visible cloud layer would be the top of a thick, dusty, stirred region, which is opaque to the light rays in the visible spectrum; therefore, no radiation reaches the surface. The upper atmospheric circulation is thermally driven, thereby transferring momentum downward and agitating the gritty nether regions. The surface is thus heated to 600° K (3-21 cm emission) by the resulting dust and gas friction in the lower atmosphere. The thermal structure, Figure 7, (a) of the upper atmosphere is much like that of Greenhouse Model "A", except the temperature of the visible cloud layer is $\underset{=}{<}$ ($\sim$340° K) 285° K (8000 Å) rather than 234° K (infrared thermocouple). The clouds are composed of very fine white powder, mostly carbonates. The far infrared and ultraviolet (234° K) arise from an unspecified but nonaqueous haze layer at 36 km. The model results in a hot, dry surface, which experiences winds as violent as those of the most relentless Earth storm. Fairly large chunks of matter are hurled about, and it is pitch dark, the sun never being visible.

In this model, an adiabatic vertical temperature gradient is needed in order to produce the turbulence necessary to raise the dust and form a self-supporting cycle. If a subadiabatic gradient existed, the proposed thick dust clouds could not exist, since the turbulence would gradually die down. Thus temperature must be a unique function of altitude. The diameter of the dust particles appear to be about 0.5 micron at the visible cloud top; and an average of approximately 200/cm^3 should exist, which may account for absorption of 8.6 mm. The pressure at the visible cloud level, P_c, is approximately 0.6 atmosphere

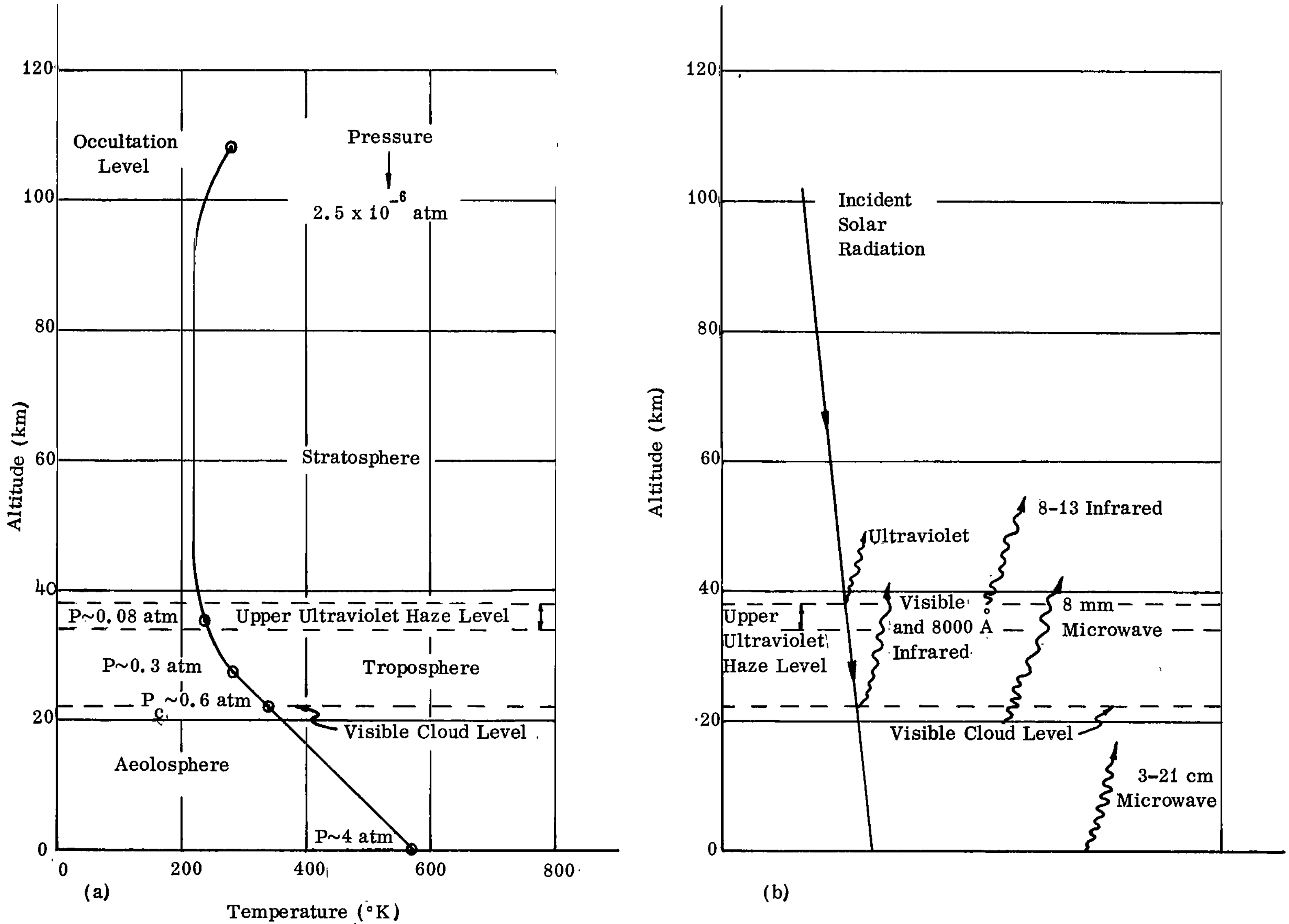


FIGURE 7. AEOLOSPHERE MODEL: (a) THERMAL STRUCTURE; (b) REFLECTING LAYERS.

at 340° K, and the upper haze is at a pressure of approximately 0.08 atmosphere and a temperature of approximately 234° K. The atmosphere is probably about 80 per cent CO_2, which would result in a surface pressure of 4.3 atmospheres. Cloud top is estimated to be at approximately 20 km. A level saturated with H_2O vapor is not expected, so no cirrus (ice-crystal) clouds should form.

In the face of apparent difficulties with the greenhouse model, this model is the only other one which attempts to account for high surface temperatures. The atmospheric water and absorbent particles appear to be insufficient to produce a greenhouse effect. A reasonable mechanism for the circulation would be different cloud top pressures which would be caused by zonal and diurnal temperature variations.

According to Öpik [40], the model agrees with the following observations: spectral-energy distribution and relative albedo from ultraviolet to red; brightness distribution across the disk in ultraviolet and red; band brightness contrast in ultraviolet and blue; polarization in visible and ultraviolet; total albedo; thermal radiation radiometry in 8 to 14 micron region; CO_2 band intensities at 0.8, 1.05, 1.20, 1.43, and 1.60 microns; continuous spectral-energy distribution in 0.76 to 1.6 micron region; strength and weakness of CO_2 bands in 9 to 11 micron region; H_2O abundance from 1.13 micron band; microwave radiation in 3 to 10 cm; indications of slow rotation; occultation of Regulus; and photometric interpretation of micrometer diameter.

This model has several inherent difficulties. Circulation details [31] have not been incorporated into the system, and it has not been demonstrated that the momentum transport necessary to heat the surface is feasible. The model disagrees with Sinton's suggested ice crystal layer. It also is inconsistent with a marked phase effect (Drake) in the microwave emission. If a massive dust cloud covers the surface, cloud temperatures should respond sluggishly if at all to a change in insolation. The microwave phase effect renders the model implausible by the following inconsistencies [11].

1. The surface is unheated by sunlight and yet the illuminated hemisphere is at a higher temperature than the unilluminated.

2. The heat source is located beneath the cloud cover, but the lowest temperatures are observed at inferior conjunction, which is when such a heat source should be most apparent.

The model was eliminated when Sagan [1] pointed out that this phase effect necessitated a dark side subadiabatic lapse rate, the existence of which made the aeolosphere impossible.

SECTION IV. ELIMINATION AND MODIFICATION OF MODELS

A. ELIMINATION OF AEOLOSPHERE AND IONOSPHERIC MODELS

In the previous section it was noted that the Aeolosphere Model was rendered implausible by the discovery of a dark side subadiabatic lapse rate. The Ionospheric Models met the same fate when two decisive measurements were made, one by Spinrad and one by Mariner II.

Spinrad [17] conducted an analysis of the 7820 Å band, which should certainly penetrate deeply into the atmosphere, and found temperatures of approximately 440°K and pressures of approximately 10 atmospheres. The high pressure indicates that this temperature must exist fairly close to the surface, and such a value is completely incompatible with Ionospheric Models. Extrapolation of this data, coupled with other measurements, results in very high surface temperatures and pressures.

Mariner II's [23] [24] microwave radiometers detected a definite limb-darkening effect. If the centimeter emission had been from the ionosphere, a limb-brightening would have ocurred. All proposed cool-surface models thus appear impossible, since these measurements indicate that the surface temperatures must be in excess of 600°K.

In addition [11], although Mariner II indicated a minute Cytherean magnetic field, it also showed that the solar plasma flux was too low to sustain the ionospheric model.

B. OBJECTIONS TO THE GREENHOUSE MODEL "A"

Several incongruities in Greenhouse Model "A" have been noted. Mintz [25] doubted that the short wave absorption could remain small enough to allow the sunlight penetrating the clouds to suffice for the maintenance of both the high surface temperature and the convection necessary to keep the cloud particles suspended. Some other circulatory difficulties have been raised. It is not known [27] if the steep vertical temperature gradient can be maintained, since vertical convection and horizontal advection should tend to somewhat equalize the temperature. Assuming the greenhouse effect existed [25], the spherical form of the planet would give rise to a large horizontal heating gradient from the equator to the poles. On a slowly rotating planet such a gradient would cause a strong meridional circulation, and the greenhouse effect would be opposed by the resulting vertical heat transport.

It is not known [27] whether the required infrared opacities can be achieved. Estimations of shielding [40] indicate that the greenhouse effect cannot support high surface temperatures, since radiation both to and from the surface is so impeded by the atmosphere that the mechanism cannot operate effectively. Also [27] there is no direct spectroscopic data on the required long paths, high temperatures, and moderately high pressures.

The main objection to the described greenhouse model is the apparent lack of the necessary water vapor. The observed pressures and temperatures from observations of the 7820 Å CO_2 band intimate that it should penetrate deeply into the Cytherean atmosphere, but Spinrad's [17] observations at this wave length found no indications of water. Without significant water vapor [40], the CO_2 atmosphere is not enough to account for the opacity needed, and it is difficult to see the formation of the required cirrus clouds.

C. GREENHOUSE MODEL "B", Figure 8

With the emergence of model difficulties, there then appeared to be no way to account for the large temperature gradient measured between the surface and the cloudtop. However [1], recent observations made with improved instruments indicate that there is a phase variation, in which a surface temperature difference between the dark and light sides of at least 70°K is indicated by all observers. Interpretation of this fact produced Greenhouse Model "B", which dictates surface conditions even more extreme than were formerly thought to exist. The phase variation necessitates a subadiabatic dark side lapse rate. By incorporating this information into model "A", Sagan derived the following conclusions.

It is estimated that the pressure at cloud level on the sunlit side is equal or greater than the pressure at the cloud level on the dark side, and that at cloudtop the CO_2 mixing rate α is approximately 0.05 -0.15 [41]. The dark side cloud altitude is 80 ± 20 km, and the altitude on the bright side should be somewhat higher. Various measurements at wavelengths from the visible to the far infrared infer that the main reflection surface is the visible cloud layer. The temperature there is 234°K, and the pressures are 90 mb on the dark side and 608 mb on the light.

At the occultation level, the temperature is 203°K and the pressure is 2.6×10^{-3} mb. These values are derived from the occultation of Regulus [42], which occurred 55 ± 8 km above the visible cloud layer.

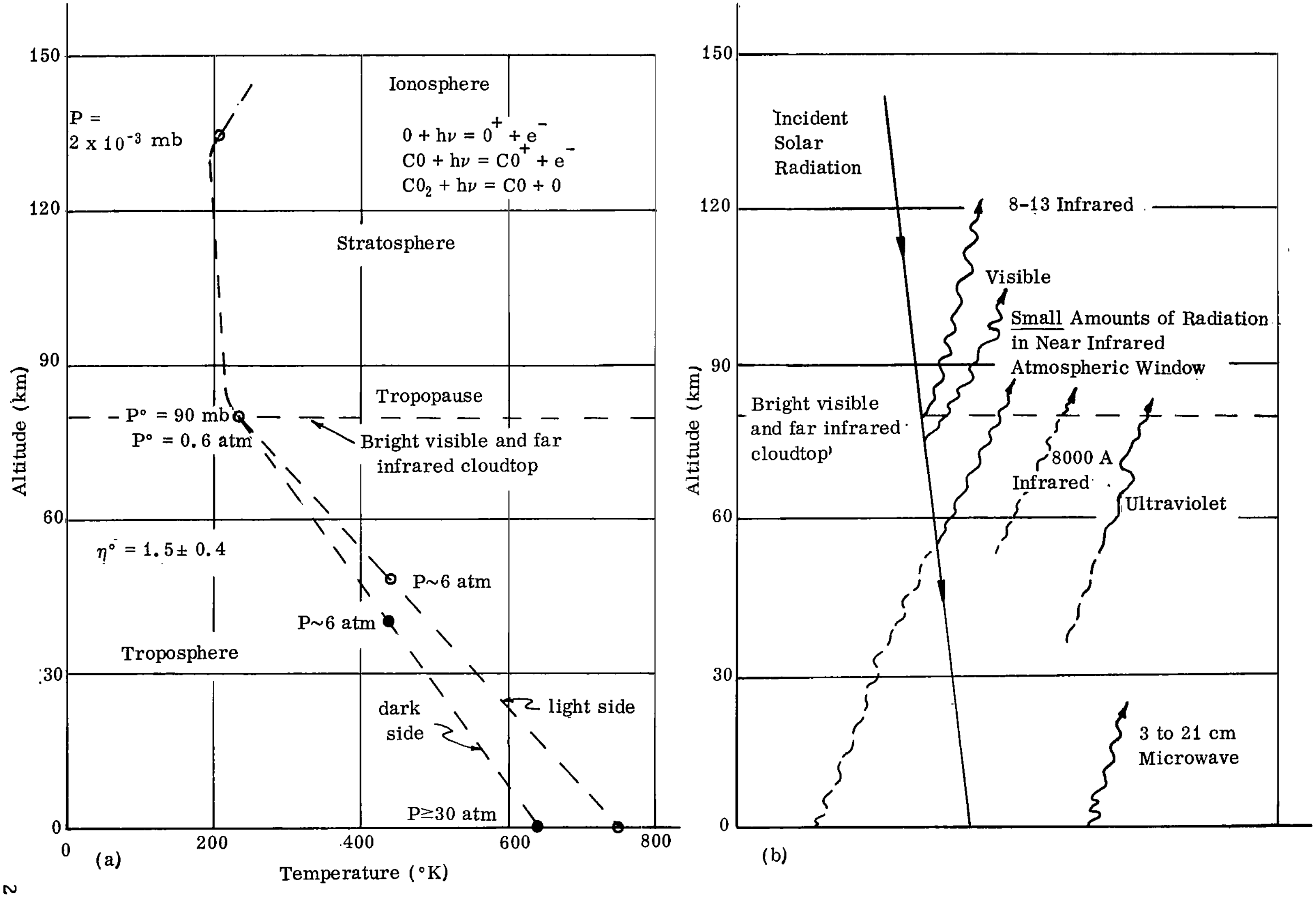


FIGURE 8. GREENHOUSE MODEL "B": (a) TEMPERATURE VS ALTITUDE; (b) RADIATION LEVELS.

Based on the radar values for emissivity [19], the bright side surface temperature is 750°K and dark side is 640°K. With a lapse rate between $\frac{1}{2}$ and 1 times the dry adiabatic lapse rate and a surface temperature of 740°K, the derived surface pressure is at least 30 atmospheres. The dark side lapse rate is estimated to be $1/1.5 \pm 0.4$ times the dry adiabatic lapse rate. It is assumed that under these conditions no significant water vapor exists. Since synchronous retrograde rotation is indicated by observations, a surface wind velocity of 0.15 -0.10 m/s is required to carry the necessary energy from the light side to the dark side. The high temperatures and pressures would provide the necessary cloud opacity by thermal excitement of low-lying rotational states, pressure broadening of line contours, and pressure induced dipole transitions and volatilization of surface material. With the resulting Rayleigh scattering, the only wave length that would reach the surface is near infrared, which could do so only in breaks in the somewhat turbulent cloud cover.

SECTION V. DISCUSSION OF THE GREENHOUSE MODEL "B"

A. FAVORABLE COMMENTS

This model removes the objections to the Greenhouse Model "A", and it is backed up by many recent observations. Analysis of the 7820 Å band of old Mt. Wilson spectra data revealed varying rotational temperatures and line contour pressures [1]. This indication of day-to-day variation in the cloud cover implies higher surface temperatures and pressures than had been previously expected. The conclusion of a single reflecting cloud is based on the fact that many observations using various wave lengths indicate about the same temperature. Any variations are probably because of fluctuations in the cloud cover. By utilizing the occultation pressure of Regulus [42], the main reflecting layer may be inferred to be the visible cloud cover [1].

There are several lines of argument to back up the conclusion of very high surface pressures. If one assumes a dry adiabatic lapse rate coupled with a surface temperature of 740°K, a surface pressure of 4.5 atmospheres is obtained; but since the lapse rate is subadiabatic, the surface pressure must be greater than 4.5 atmospheres. The surface temperature used in this calculation is based on black-body microwave readings of about 660°K and radar measurements [19] which show an emissibity of about 0.9, thus inferring a surface temperature of about 740°K. Also [1], if indicated microwave attenuation at greater than 3 cm is actually significant, and if the bright cloud top pressure is really greater than the dark side cloud top pressure, the attenuation will raise the surface temperature and the pressure differences will raise the surface pressure. Calculations made with the various possible parameter values result in surface pressures as high as several hundred atmospheres.

An independent method of deriving high surface pressure [1] is based on the breakdown of the Urey equilibrium. By assuming that Earth and Venus had the same initial amount of CO_2, a partial pressure for CO_2 of 16 atmospheres may be obtained; and if the atmosphere is assumed to be 20 per cent CO_2 and 80 per cent N_2, the resulting surface pressure is 55 atmospheres. If the mixing ratio is assumed to be 0.05, as indicated by Regulus occultation, a surface pressure of 210 atmospheres is obtained.

A third method of deriving high surface pressures [1] is by consideration of the reduction of the 7820 Å band. By assuming that the cloud deck has a sharp upper boundary and that the distribution of scatterers does not follow the distribution of absorbers, consistent values for temperature may be obtained from the distribution of the intensity of the rotational components of the band. The pressure at the bottom of the band is found to be about 10 atmospheres and the temperature is 440°K. Upon assuming a surface temperature of 670°K, this information indicates surface pressures of 27 and 42 atmospheres; while if a surface temperature of 800°K is assumed, the resulting surface pressures are 55 and 82 atmospheres. If the lower atmospheric lapse rate is assumed to be subadiabatic, surface pressures lower than 30 atmospheres are impossible to derive.

The Rayleigh scattering resulting from this model should yellow the sky [1], thus explaining the color of Venus. This color should be a function of phase.

Both visual and photographical studies and near infrared spectroscopy indicate [1] that moments of clearing do occur, in spite of measurements at 8-13 μ which indicate a 99 per cent cloud cover. With the high surface pressures, clouds as high as 40 to 50 km may be affected by surface features. These lower clouds may not be seen in the visual spectrum because of Rayleigh scattering, but they could be photographed in ultraviolet. Near infrared could observe these clouds, and the lower surface as well, through a break in the cloud cover.

Ohring [30] made some calculations relating the magnitude of the greenhouse effect to the cloudiness and opacity of the atmosphere by assuming that Venus has a grey atmosphere and an extensive cloud cover that is opaque to infrared but transparent to solar radiation that is not reflected by the cloudtop. He also assumed an adiabatic lapse rate. From this he concludes that a 600°K surface temperature may be maintained by the greenhouse model with utilization of the opaque clouds and the CO_2 concentration and that there is no need for any additional absorption molecules, although such a molecule would enhance the greenhouse effect and cut down the requirements for cloudiness or CO_2 or both.

On a planet with synchronous rotation, such as Venus, the energy radiated to space must be replaced, in the steady state, by an energy transport from the bright side. By use of the gas laws and the nearly constant infrared temperature of 225°K, Mintz [38] has calculated the wind velocity necessary to maintain balance in the greenhouse model. It is from this that the estimated surface wind velocity is obtained.

Mariner II infrared radiometer measurements showed no breaks in the cloud cover [11]. This indication of small lower atmospheric heat loss is important, since that is the basic requirement for the greenhouse effect.

B. MODEL INCONGRUITIES

Several doubts still exist about this final Greenhouse Model "B". All methods of establishing it suffer from lack of observational material [1]. Harteck [39] has indicated that chemical reactions which should occur in the Cytherean atmosphere may be responsible for some of the microwave emissions. Cloud composition and thickness are uncertain [30]. The amount of radiation absorbed by the clouds has not been resolved, and with surface pressures of perhaps 50 atmospheres, it is not known how much radiation ever reaches the ground.

A new interpretation by Kaplan [43] of old 0.78 μ data results in a lower surface pressure than has been indicated by this model, but these results are not necessarily conclusive. Also, Mariner II data [23] [24] indicate an insignificant phase effect, but recent microwave observations by Drake [22] appear to contradict that data.

The question of water vapor in the Cytherean atmosphere has been reopened by the recent balloon observations made by Strong [50]. Measurements were made of the 1.13 μ radiation from Venus by an automatic telescope which was carried to an observational altitude of 26.5 kilometers. The modulation produced by water absorption was (10.5 ± 0.5) percent, which calibration reveals as equal to that produced by 9.8×10^{-3} gm/cm^2 of water vapor at atmospheric pressure. Assessments indicate that only about 1/20 of the modulation can be attributed to telluric water vapor. If a cloud top pressure of 90 mb is assumed, then there exists 22.2×10^{-3} gm/cm^2 water vapor, with a mixing ratio of 2.5×10^{-4}. Assuming a 600 mb pressure, the derived values are 5.2×10^{-3} gm/cm^2 and the mixing ratio is 0.87×10^{-5}. Exact results must await pressure data, but the geometric mean of the two noted extremes represents values reported for comparable levels in the Earth's upper atmosphere (M. Gutnick, Air Force Survey in Geophysics, No. 147). Thus this measurement could conceivably require re-evaluation of atmospheric temperature distribution estimates.

There is also a circulation problem with this model. With the bright side cloud top pressure greater than that on the dark side plus equal temperatures on both sides at cloud top, it is difficult to see the assumption of a higher cloud top altitude on the light side. Such conditions would appear to result in tremendous winds and turbulences which are not confirmed by observation.

At any rate, this model presently appears to be the most valid. Some parameters established by Greenhouse Model "B" are presented in Appendix A.

SECTION VI. CONCLUSIONS ON SURFACE CONDITIONS ON VENUS

Thus, the surface of Venus appears to be a forbidding place, with surface temperatures comparable to a red-hot oven and pressures that exist on Earth only at ocean depths greater than 350 meters. Since the melting points of aluminum, lead, tin, magnesium, zinc, and bismuth might be reached [1], pools of molten surface material could cover much of the bright side. The high pressures may produce clouds of exotic materials that would ordinarily be gases at such temperatures. The temperature of the dark pole has been estimated by Drake to be 540°K, and with the high surface pressures, several possible constituents of the lower atmosphere may condense out in that region. Such polar seas may contain liquid benzene, liquid acetic acid, liquid butyric acid, liquid phenol, and if the pressure exceeds 60 atmospheres, perhaps a bit of liquid water. If ammonium chloride is present, it will condense out over most of the dark hemisphere; and the reaction of N_2, $C0_2$, and H_20 can be expected to produce surface organic matter. However, N_2 and $C0_2$ will remain in the gas phase at all times. If this model is valid, a surface landing presents an engineering problem of a magnitude never encountered before.

APPENDIX A. PARAMETERS RESULTING FROM GREENHOUSE MODEL "B"

Parameter	Minimum	Maximum	Most Probable
Surface Temperature (dark side)	(Drake) 540°K (at pole)	640°K	610-640°K
Surface Temperature (light side)	700°K	800°K	750°K
Temp. at Cloud Top	---	---	234°K
Albedo	0.6	0.76	0.76
Cloud Top Height	60 km	100 km	80 km
Water Content	0 %	22.2×10^{-3} gm/cm^2	Insignificant
Surface Pressure	30 atm	Several 100 atm	50 atm
Cloud Top Pressure	90 mb (dark side)	0.6 atm (608 mb) (light side)	Dependent on Hemisphere
Surface Wind Velocity	0.3218 km/hr	0.4827 km/hr	Very light
Height of Occultation	107 km	163 km	135 km
Occultation Temperature	195°K	216°K	203°K
Occultation Pressure	2.4×10^{-3} mb	2.9×10^{-3} mb	2.6×10^{-3} mb
Density (gm/cm^3)	1.325×10^{-3} (cloud top)	2.607×10^{-2} (surface)	6.5476×10^{-3} (in cloud layer)
Molecular Weight	29.6	29.6	29.6
Sp. Ht. Ratio	1.347 (surface)	1.4 (cloud top)	1.389 (in cloud layer)
Speed of Sound (km/sec)	0.3056 (cloud top)	0.5278 (surface)	0.4166 (in cloud layer)
Value of α where volume mixing ratio is α CO_2 to $(1-\alpha)$ N_2	0.05	0.20	0.15

(References: 1, 40, 38, 45, and 50)

APPENDIX B. RELATED EQUATIONS AND RESULTS

Section I

Jones [32], in investigating an isothermal layer at $\bar{e}$ temperature Te, found that an effective temperature $T_b = T_e (1-e^{-\Delta}) + T_s e^{-\Delta}$ where T_s = surface temperature, and Δ is the opacity (for $Z = 1$ and $n_e = n_i$) and $= 1.98 \times 10^{-23} g\lambda^2/T_e^{3/2} \int n_e^2 dz$ where g = Gaunt factor (~ 4). By assuming $T_e \sim 600°K$, $T_s \sim 265°K$, and $\int n_e^2 dz \sim 10^{25}/cm^5$, a good data fit is obtained.

In investigation of the effect of solar corpuscular radiation on such a layer, Jones found that $\alpha \int n_e^2 dz \sim 10^{13}/cm^2$ sec (for oxygen at 600°K). Since there are $\sim 10^3$ protons/cm^3 entering the atmosphere at $\sim$750 km/sec, a flux of $\sim 7.5 \times 10^{10}$ protons/cm^2 sec is obtained. Since such particles have energies on the order of kilovolts, they could easily maintain the emitting layer in the ionospheric model.

Section II

In Greenhouse Model "A," Sagan's [29] equation for radiation balance at the top of the atmosphere is as follows:

$$\sigma T_e^4 = \sigma T_a^4 + (1 - \alpha) \sigma T_s^4$$

where σ = Stefan-Boltzmann constant, T_e = effective temperature of incoming solar radiation (allowing for albedo losses), T_a = effective radiating temperature of atmosphere, T_s = surface temperature, and $(1 - \alpha)$ = transmissivity of atmosphere for infrared.

Taking $T_s = 600°K$, $T_e = 254°K$, and $T_a = 234°K$, $(1 - \alpha)$ is found to be 0.9 per cent. By making use of laboratory emissivity measurements, 18 km STP of CO_2 and 9 gm/cm^2 of H_2O is found to produce this transmissivity.

Section III

Jastrow and Rasool, in computing the same radiative equilibrium temperature distribution as Sagan computed [29], make use of the Eddington approximation to derive the following:

$$T_s = T_e (1 + .75\,\tau_g)^{1/4}$$

where τ_g = atmosphere opacity in infrared. When $T_s = 600°K$ and $T_e = 254°K$, τ_g is found to be about 40. The equivalent transmissivity = exp $(-\tau_g) = 10^{-17}$, which is far less than Sagan's value.

The discrepancy arises from Sagan's choice for T_a, since if one substitutes 10^{-17} for $(1 - \alpha)$, T_a is found to be 254°K.

Section IV

Ohring [30] has made calculations for radiation balance in which the cloud opacity is considered, and he has derived the following equation: transmissivity (for infrared) $t = [T_e^4 - n\,T_c^4 - (1-n)\,T_a^4]/(1-n)\,T_s^4$ where n = fraction of sky covered by clouds, T_c = cloud top temperature, and T_a = effective radiating temperature for the clear part of the atmosphere.

By substituting $T_s = 600°K$ and $T_c = 235°K$, values for t may be found by using various values for n. T_e may be either 254°K or 237°K, depending on the albedo value used. T_a is made to vary between 235°K and the temperature at which t equals zero. In the following results, n is allowed to equal 0, 0.80, 0.90, 0.95, and 0.99, and t is tabulated versus various values of T_a.

$T_e = 254°K$
(t is in %)

	n				
T_a (°K)	0	0.80	0.90	0.95	0.99
0	3.2				
100	3.1				
200	2.0				
235	1.0	4.3	8.5	17.1	85.9
250	0.2	3.6	7.9	16.4	85.2
275		2.2	6.5	15.0	83.8
300		0.4	4.7	13.2	82.0
325			2.3	10.8	79.6
350				8.5	76.6
375				4.1	73.0
400					68.4
450					56.6
500					40.0
550					17.6

$T_e = 237°K$

T_a (°K)	n = 0	0.80	0.90	0.95	0.99
0	2.4				
100	2.4				
200	1.2				
235	0.1	0.4	0.8	1.6	8.1
250			0.2	1.0	7.4
275					6.0
300					4.2
375					1.8

Section V

Ohring [30] also relates the magnitude of the greenhouse effect to atmosphere cloudiness and opacity. In the derivation of this equation, it is assumed that Venus has a grey atmosphere and an extensive cloud cover which is transparent to solar radiation that is not reflected by the cloud top but is opaque to infrared radiation. On this basis, the equation is found to be as follows:

$$(T_e/T_s)^4 = n\,p/3 \left[2/p\,\tau_s\,[1-\exp(-p\,\tau_s)] + 2E_3\,(p\,\tau_s)\right] + (1-n)/3 \left[2/\tau_s\,[1-\exp(-\tau_s)] + 2E_3\,(\tau_s)\right]$$

where p = pressure, τ_s = atmospheric infrared opacity at surface, and E = exponential integral. T_s/T_e may then be calculated through a wide range of values for p, τ_s, and n.

Assuming that $T_s > 600°K$, $T_s/T_e > 2.5$ if $T_e = 237°K$, a value which corresponds to an albedo of 0.73. Sagan has estimated that $P_c° \sim 90$ mb, $P_c° \sim 0.6$ atm, and 30 atm$\leq P_s \leq$ several hundred atmospheres. Assuming P_c 0.6 atm and $P_s = 60$ atm, p = 0.01. By utilization of these values, the following opacities are found: at n = 0.80, $\tau_s = 7.4$; at n = 0.90, $\tau_s = 1.8$. These values correspond to transmissivities of 6×10^{-4}, 1.8 per cent, and 16 per cent, respectively.

Plass and Stull (1963) have shown that a transmissivity of 10.4 per cent will result from a CO_2 content of 10^6 cm STP and an average slant path pressure of 10 atmospheres. This value is well within the 16 per cent allowed with 95 per cent cloudiness. Since estimations of cloud cover generally run about 99 per cent, it is concluded that the combined effect of CO_2 and cloudiness will suffice for the maintainence of the greenhouse effect, and thus no absorbing molecule is required.

Section VI

Sagan [29] has calculated the water vapor Q above an ice layer at temperature T_o by the following formula:

$$Q = 4 \times 10^{-7} P_o T_o$$

where P_o = vapor pressure (dynes/cm^2) corresponding to T_o.

He obtains the following results:

H_2O vapor above surface	Resulting T_c	Q
1 gm/cm^2	220°K	2.4×10^{-3} gm/cm^2
3	225	4.5×10^{-3}
10	233	1.2×10^{-2}

The assumed surface water vapors are based on best guesses for synchronous and non-synchronous rotation, where for non-synchronous the value ~ 9 gm/cm^2 and for synchronous the value ~ 1-2 gm/cm^2. Nine gm/cm^2 is used in Greenhouse Model "A" since at that time it was felt that non-synchronous rotation was more likely. This was based on the estimation that Venus was formed with 10^4 -10^5 less water than Earth, so the greatly reduced solar tidal friction would render synchronous rotation unlikely.

The balloon observations of Moore and Ross indicate that Q is between 1.5×10^{-3} and 3.0×10^{-3} gm/cm^2. The results of observation and calculation agree if synchronous rotation is assumed and T_c is allowed to be 14°K cooler than the thermocouple temperatures. T_c can be made to agree with the thermocouple measurements if Q is allowed to be 1/5 that derived from the above equation. Emission of CO_2 bands in the 8-13 μ region arising from an altitude and temperature higher than the cloud layer would explain the 14°K difference. In the case of agreeable temperatures, photodissociation could produce a water vapor abundance < saturation.

Section VII

Urey has derived a water diffusion rate which with photodissociation could account [29] for the present CO_2 abundance. However, calculations solving for diffusion rate by

$$J = D \rho 1^{-I} (I - e^{-4H/1})^{-I}$$

(where 1 = scale height corresponding to μ (atm) $- \mu$ (H_2O), ρ = mass density of H_2O vapor immediately above cloud layer, and D = diffusion coefficient) result in a conflicting rate if Strong's water measurements are used.

If the amount of water vapor above the cloud layer were the saturation value and if the cloud layer were at 8 to 13 μ temperature, the two diffusion rates would agree, but if Strong's value is correct, the rate would be such that the CO_2 abundance cannot be explained by the photodissociation of the water vapor during geological times.

Section VIII

It is proposed [46] that the chemiluminescence of the Venus airglow results from the reaction of carbon monoxide and atomic oxygen via the following mechanism: (the overall combination reaction is spin-forbidden)

$$CO(^1\Sigma^+) + O(^3P) \rightarrow CO_2(^1\Sigma^+_g)$$

if spin reversal occurs in the stabilization of the excited CO_2 molecules by a third body:

1. $O + CO \xrightarrow{k_1} CO_2^+$
2. $CO_2^+ + M \xrightarrow{k_2} CO_2^* + M$
3. $CO_2^+ + M \xrightarrow{k_3} CO_2 + M$
4. $CO_2^* + M \xrightarrow{k_4} CO_2 + M$
5. $CO_2^* \xrightarrow{k_5} CO_2 + h\nu$

Section IX

The prediction of the temperature of a hypothetical airless planetary surface is possible [11] if the reflectivity of the surface and the local solar constant are known. With a reflectivity A which is obtained from values averaged over all wavelengths and a solar constant S, it is apparent that S (1-A) units of solar energy will be absorbed per unit surface and time. At equilibrium, this is also the flux radiated back into space.

Therefore $\sigma T^4 = \frac{1}{4} S(1-A)$

where σ = Stefan-Boltzmann constant.

Knowing the solar constant for Earth, the visual reflectivity for the clouds of Venus, and the distances of Venus and Earth from the sun, a temperature of 235°K is obtained. Since this is very close to the cloudtop temperatures found in the middle infrared region, the ionospheric model seems unlikely.

APPENDIX C. TABULATION OF PHYSICAL CHARACTERISTICS OF VENUS

Mean Distance From Sun (A)	0.723332 AU
Inclination of Orbit to Ecliptic (I)	3.39426°
Longitude of Perihelion (ϖ)	131.04934°
Longitude of Ascending Node (Ω)	76.34597°
Eccentricity of Orbit (e)	0.006791
Mean Daily Motion (n)	1.602130°
Longitude (Dec. 2.0, 1962)	80.797861°
Orientation of Rotation Axis	~ Perpendicular to ecliptic
Mean Orbital Velocity	35.05 km/sec
Mean Solar Constant	3.82 cal/cm^2 min
Sidereal Period	224.701 days
Synodic Period	583.92 days
Rotational Period	~ 225 days (retrograde)
Mass	4.8734 x 10^{27} grams
Mean Density	5.15 ± 0.07 gm/cm^3
Mean Surface Gravity (at latitude 45°)	885.5 cm/sec^2
Apparent Radius	6100 km
Estimated Actual Radius	6020 km (based on assumed cloud top at 80 km)

APPENDIX C. (Cont'd)

Color	Extremely pale yellow
Mass Venus/Mass Sun	1/408539
Perihelion Distance	0.718 AU
Aphelion Distance	0.728 AU

(References: 1, 3, 44, 47, 48, 49)

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